Radiative Forcing

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293

Goals:

- Understanding interaction between gases and IR radiation
- Radiative forcing of greenhouse gases
- Radiative forcing of aerosols

Wavenumber = 1 / Wavelength

1 μm (micron) = 10^{-6} m
1 nm (nanometer) = 10^{-9} m

Therefore, 1 μm = 1000 nm

Lecture 7

19 September 2024

Announcements

1) Problem Set 2 is posted; due a week from today

2) All but the last part of Problem Set 2 can be completed following today's lecture

3) Please have a look at part f) of Problem Set 2 before next Tuesday's lecture

4) Will hold review of Lectures 1 to 9 on Tuesday, 1 Oct

5) Exam is Thursday, 3 Oct:
   - If held in class, will be closed book / no notes
   - Will focus on ***concepts*** much more than ***calculations***, although a very simple calculation-type question could possibly appear

Lecture 3

Atmospheric Radiation

THE GREENHOUSE EFFECT 23

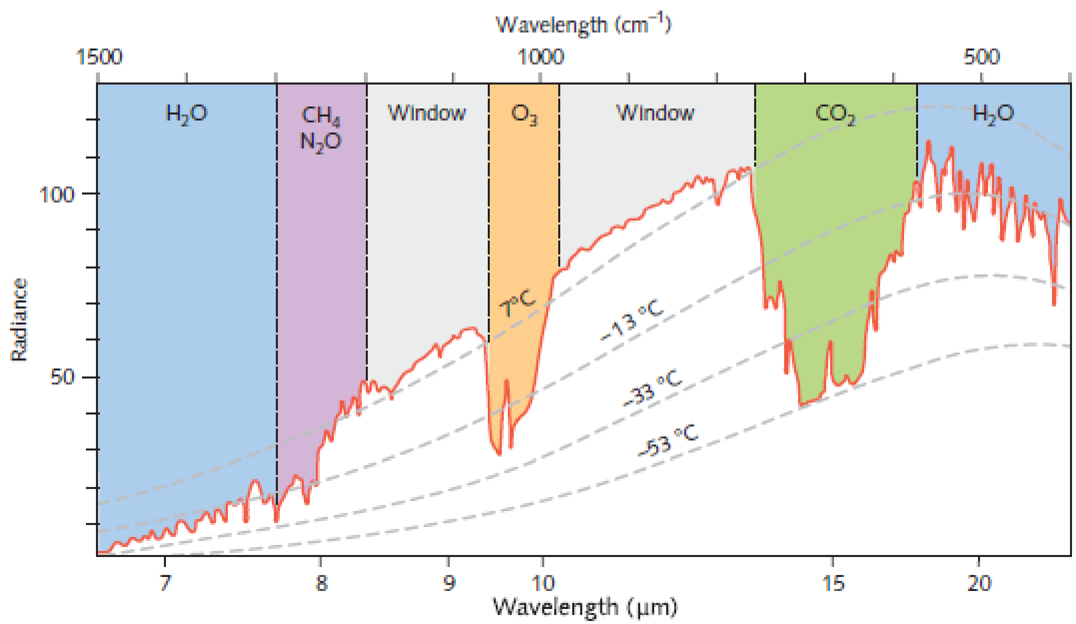
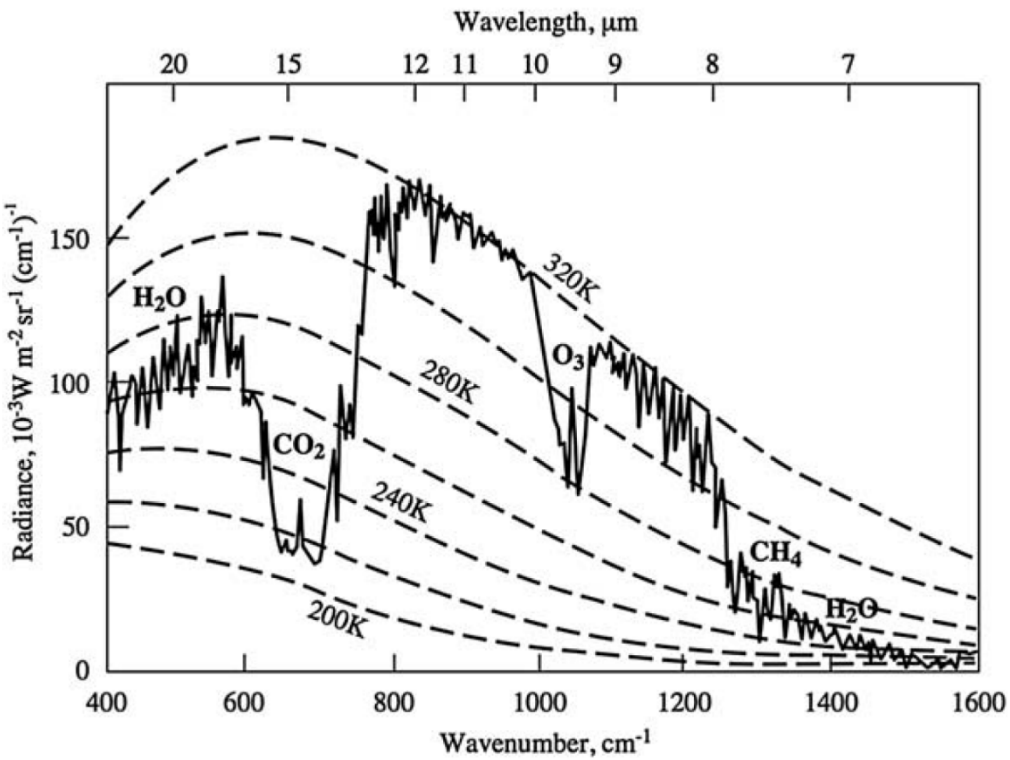


Figure 2.5 Thermal radiation in the infrared region (the visible part of the spectrum is between about 0.4 and 0.7 μm) emitted from the Earth's surface and atmosphere as observed over the Mediterranean Sea from a satellite instrument orbiting above the atmosphere, showing parts of the spectrum where different gases contribute to the radiation. Between the wavelengths of about 8 and 14 μm, apart from the ozone band, the atmosphere, in the absence of clouds, is substantially transparent; this is part of the spectrum called a 'window' region. Superimposed on the spectrum are curves of radiation from a black body at 7°C, –13°C, –33°C and –53°C. The units of radiance are milliwatts per square metre per steradian per wavenumber.

Fig 2.5, *Global Warming (5th Edition)*, Houghton

Overview



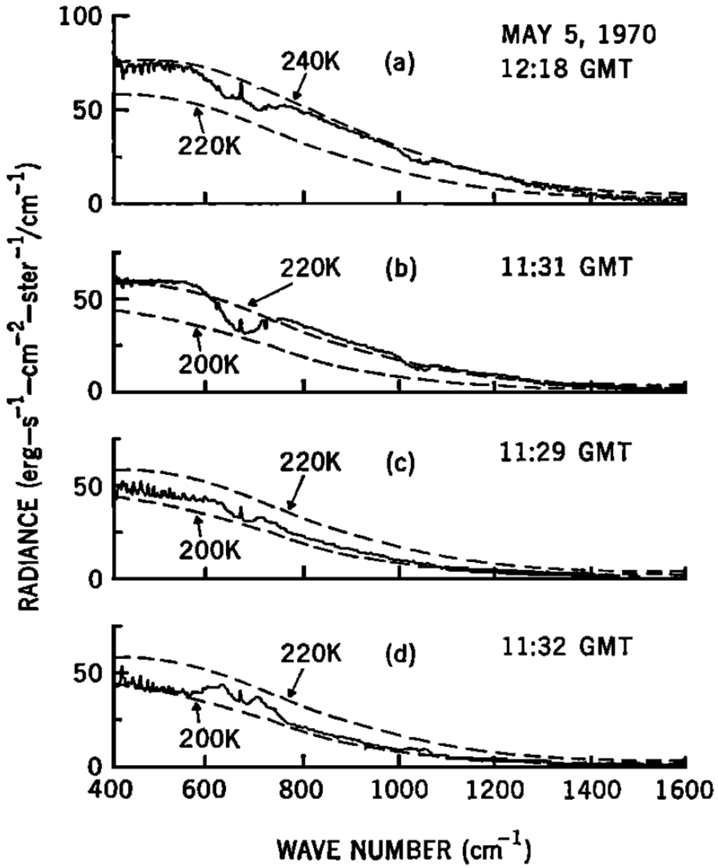
Hanel *et al*., JGR, 1972:

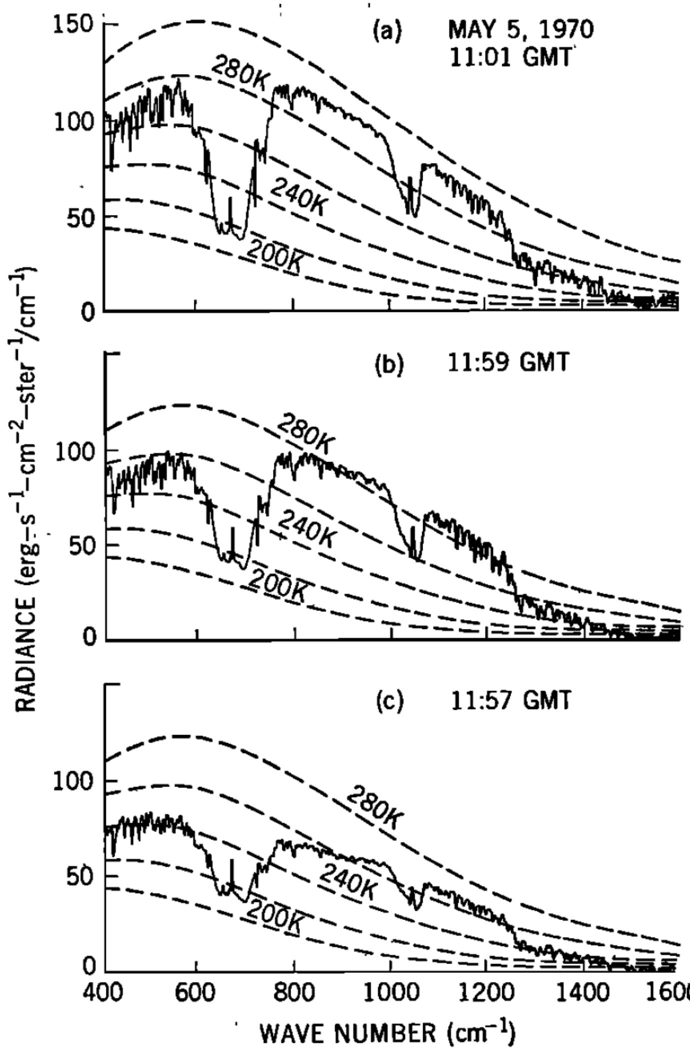
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

Viewed from space and averaged over space and time, Earth emits ~238 W/m^2 of thermal radiation between wavelengths of 5 and 50 μm.

The terrestrial emission spectrum matches that of a combination of blackbody spectra of temperatures between 220 and 320K.

The four most important gases that absorb terrestrial radiation (H_2O, CO_2,CH_4, O_3) are noted.





Hanel *et al.*, JGR, 1972: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

Overview

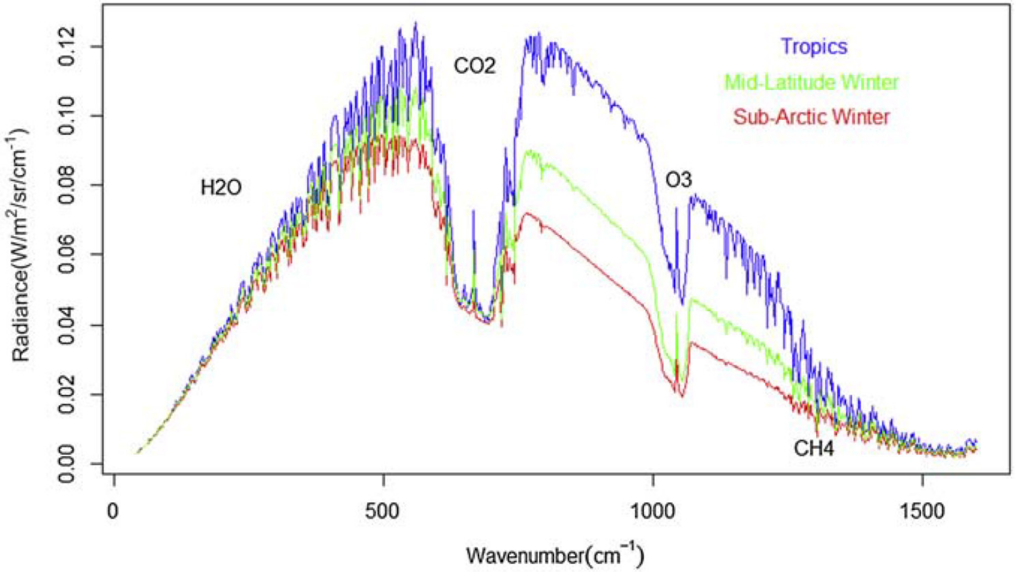


FIGURE 3.4.5 Overview of the earth's outgoing infrared radiation as a function of wave number (the inverse of wavelength) and latitude.[43] Radiances for this figure were calculated using Modtran and a web interface developed by David Archer available here: http://climatemodels.uchicago.edu/modtran/.

Kirk-Davidoff, Chapter 3.4, *Green Chemistry: An Inclusive Approach*, 2018

- GHGs prevent outgoing energy emitted from the surface from being released back into space, thereby trapping this energy and releasing it in the form of heat.
- Averaged over space and time, the Earth radiates to space an amount of energy consistent with that of a black body at 255 K.
- Some spectral regions are nearly filled (i.e., 667 cm^{-1}) whereas many others exhibit negligible attenuation of outgoing radiation.
- A newly discovered “miracle compound” with a long atmospheric lifetime will be much more damaging to Earth’s climate system if it absorbs in a region that is _____, rather than a region that is _____.

Global Warming Potential

Table 3.2 Examples of Greenhouse Gases

Name and Chemical Formula	Preindustrial Concentration (1750)	Concentration in 2008	Atmospheric Lifetime (years)	Anthropogenic Sources	Global Warming Potential
carbon dioxide CO_2	270 ppm	388 ppm	50-200*	Fossil fuel combustion, deforestation, cement production	1
methane CH_4	700 ppb	1760 ppb	12	Rice paddies, waste dumps, livestock	21
nitrous oxide N_2O	275 ppb	322 ppb	120	Fertilizers, industrial production, combustion	310
CFC-12 CCl_2F_2	0	0.56 ppb	102	Liquid coolants, foams	8100

*A single value for the atmospheric lifetime of CO_2 is not possible. Removal mechanisms take place at different rates. The range given is an estimate based on several removal mechanisms.

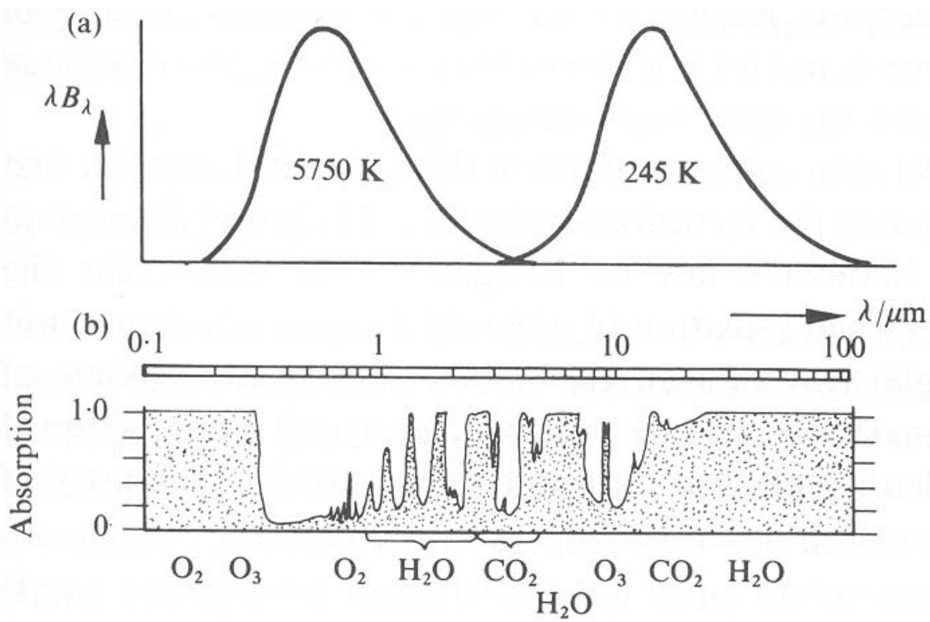
Chapter 3, *Chemistry in Context*

100 year time horizon

Some GHGs are much more effective than others, in terms of GWP (i.e., perturbation of RF per mass)

Atmospheric Radiation

- Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)
- Thermal irradiance (upwelling) at top of the atmosphere occurs at wavelengths between ~5 and 50 μm (~245 K "black body" temperature for Earth's atmosphere)



Panel (a): Curves of black-body energy versus wavelength for 5750 K (Sun's approximate temperature) and for 245 K (Earth's mean temperature). The curves are drawn with equal area since, integrated over the entire Earth at the top of the atmosphere, the solar (downwelling) and terrestrial (upwelling) fluxes must be equal.

Panel (b): absorption by atmospheric gases for a clear vertical column of the atmosphere (1.0 represents complete absorption).

From Houghton, *Physics of Atmospheres*, 1991

- Absorption and photodissociation in the UV occurs due to changes in the electronic state (orbital configuration of electrons) of molecules
- Absorption and re-emission in the IR occurs due to changes in vibrational and rotational states of molecules with electric dipole moments

Radiation & Molecules

Radiation can induce photo-dissociation (Mar 10 lecture), vibration, and rotation of molecules.

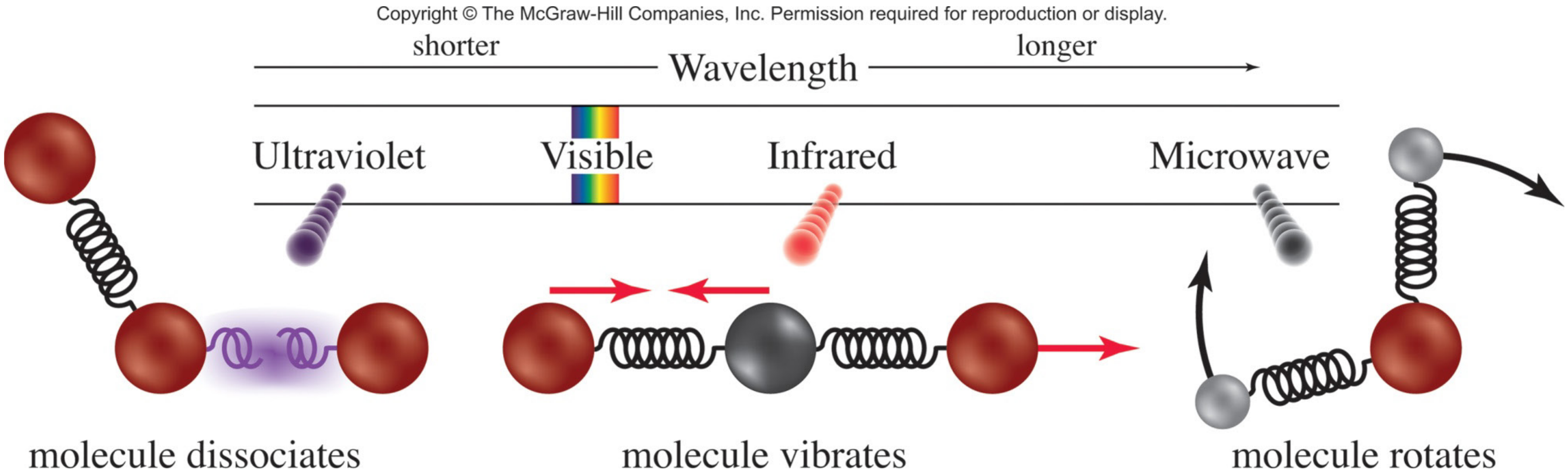


Fig 3.19, Chemistry in Context

Radiation & Molecules

Radiation can induce photo-dissociation, **vibration**, and rotation of molecules.

Thermal IR radiation is not energetic enough to break molecular bonds (i.e., photo-dissociate). Upon absorption, thermal IR will increase the vibrational energy of a molecule

CO_2 (linear molecule) has 4 vibrational modes (see below): for molecules vibrational frequencies are quantized. That is, only certain energies for the system are allowed. Most importantly, only photons with certain wavelengths (energies) will excite molecular vibrations.

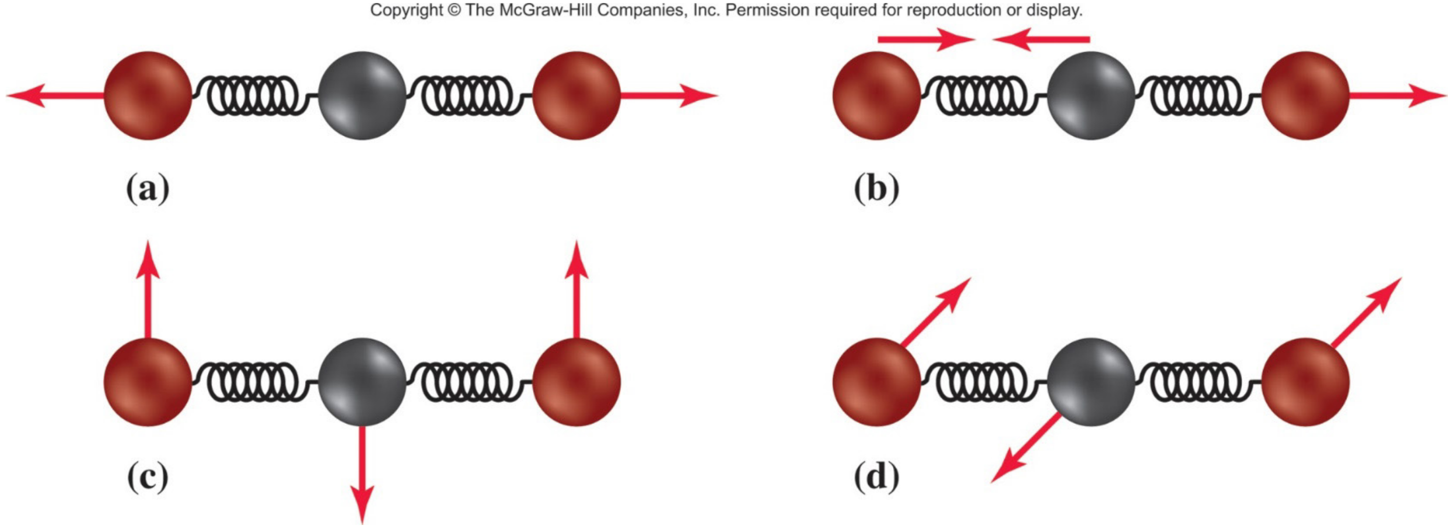


Fig 3.16, Chemistry in Context

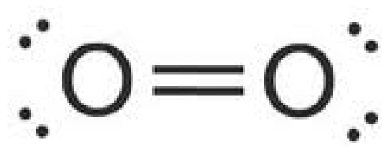
Excitation of Molecules

A greenhouse gas must have either

- naturally occurring **dipole moment**
- exhibit a **dipole moment** during vibration

Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero
spatial distribution of charge

No dipole moment, either naturally or during vibration:



Excitation of Molecules

A greenhouse gas must have either

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Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

CO_2 has ho natural dipole moment

$O^- — C^+ — O^-$

DP = 0

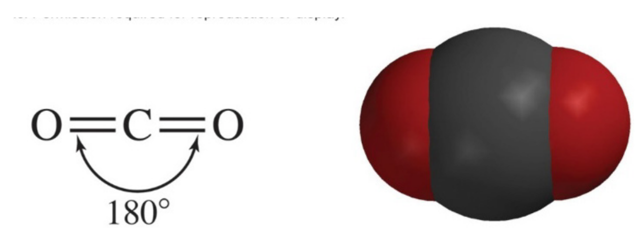


Fig 3.14, Chemistry in Context

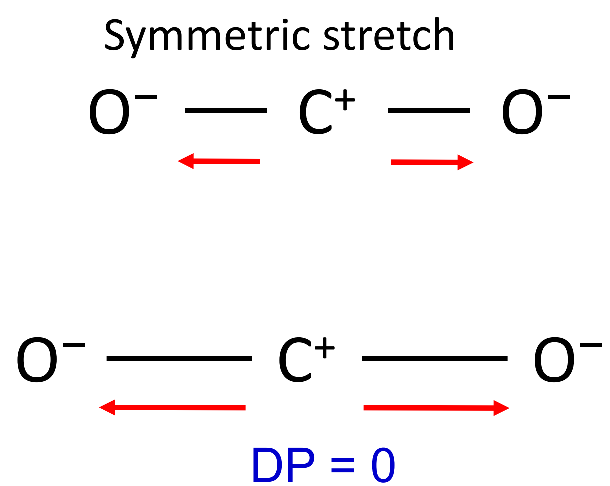
Excitation of Molecules

A greenhouse gas must have either

- naturally occurring **dipole moment**
- exhibit a **dipole moment** during vibration

Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

Symmetric Stretch: no dipole moment



Excitation of Molecules

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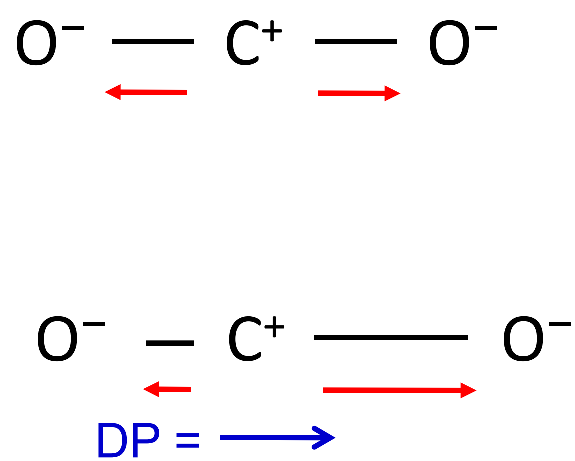
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

Anti-symmetric Stretch: *dipole moment*

Anti-symmetric stretch



Excitation of Molecules

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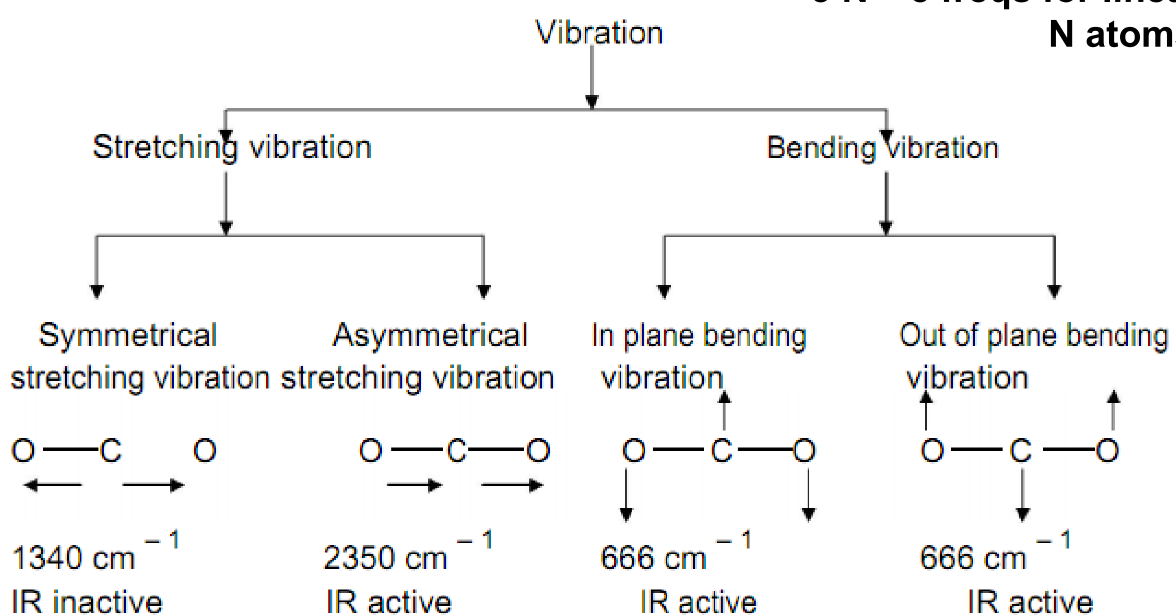
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges: i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

3 N – 5 freqs for linear molecules, N atoms: 4 freqs for CO_2



http://www.vidyarthiplus.in/2013/12/cy6151-engineering-chemistry-1.html#.VOUqai4RXIY

Excitation of Molecules

Wavenumber = 1 / Wavelength

1 / 2350 cm^{-1} = 4.25×10^{-4} cm = 4.25×10^{-6} m = 4.25 μm
1 / 666 cm^{-1} = 1.50×10^{-3} cm = 15.0×10^{-6} m = 15.0 μm

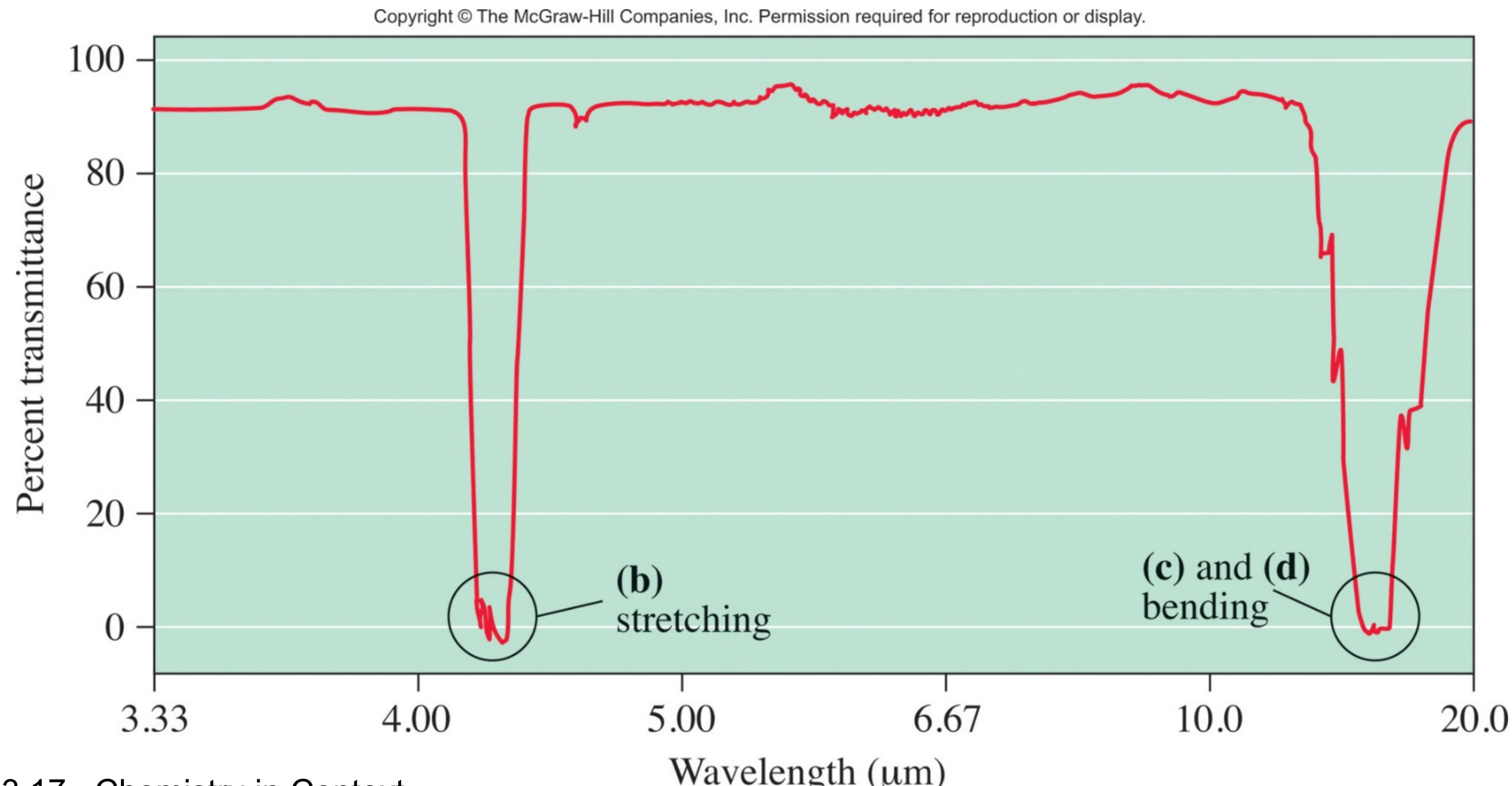


Fig 3.17, Chemistry in Context

Excitation of Molecules

A greenhouse gas must have either

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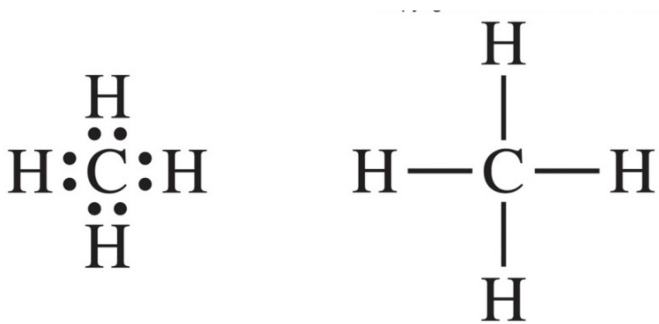
- exhibit a **dipole moment** during vibration

Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

CH_4 also has no natural dipole moment: charge is uniformly distributed



Figs 3.10 & 3.11, Chemistry in Context

Excitation of Molecules

A greenhouse gas must have either

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Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
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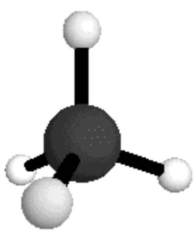
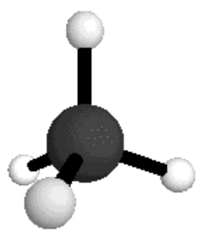
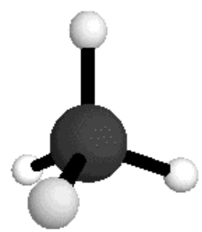
CH_4 has 4 unique vibrational modes, 2 of which interact with the IR field



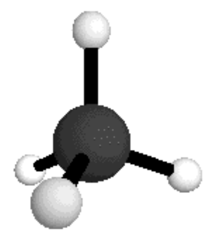
#1
3.3 μm



#2
6.3 μm



#3
3.2 μm



#4
7.6 μm

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CH4_html/CH4_page.html

Excitation of Molecules

A greenhouse gas must have either

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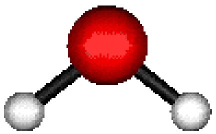
- exhibit a **dipole moment** during vibration

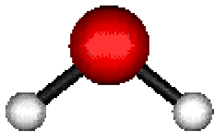
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges: i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

H_2O has a natural dipole moment (bent molecule) and absorbs in three spectral regions:



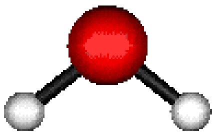
2.5 μm

Asymmetric Stretch



2.6 μm

Symmetric Stretch



6.1 μm

Bending Mode

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/H2O_html/H2O_page.html

Excitation of Molecules

A greenhouse gas must have either

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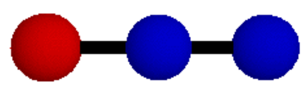
- exhibit a **dipole moment** during vibration

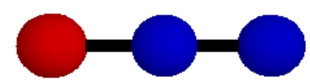
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

N_2O also has a natural dipole moment (since it is an asymmetric molecule) and also absorbs in three spectral regions:

4.5 μm



7.8 μm



17.0 μm

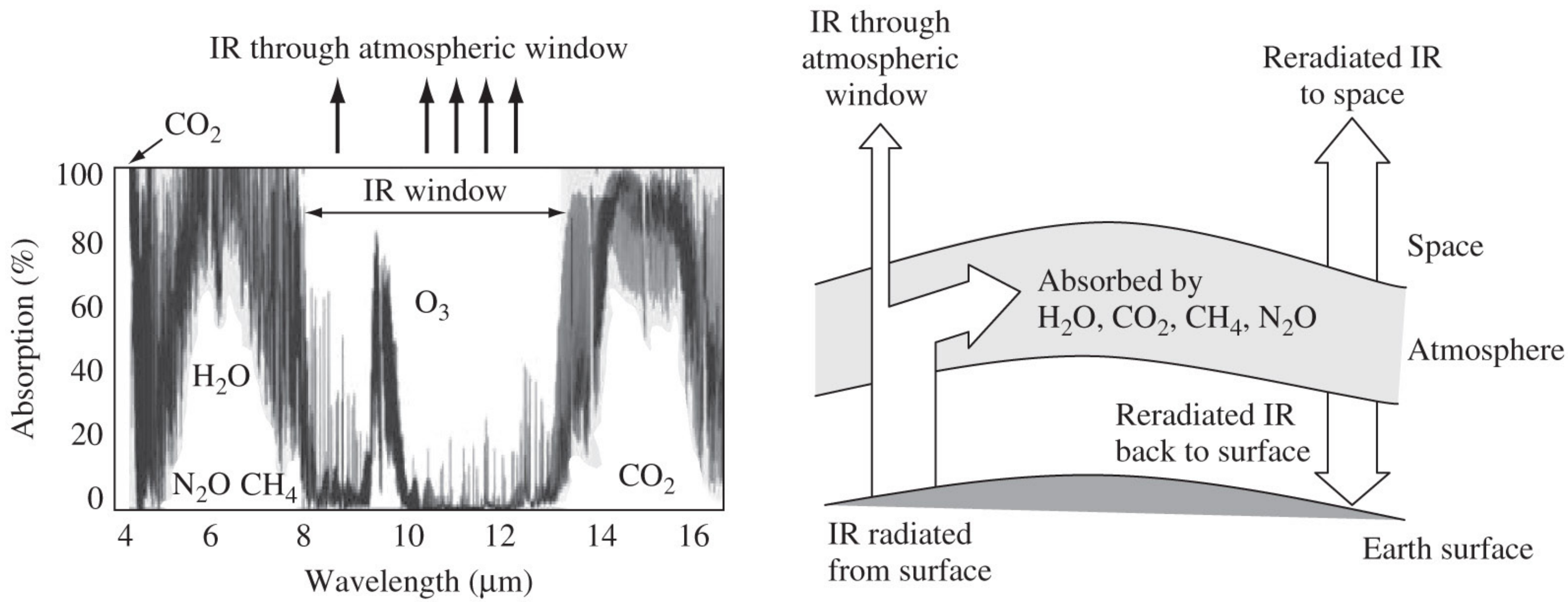
http://www2.ess.ucla.edu/~schauble/MoleculeHTML/N2O_html/N2O_page.html

The Greenhouse Effect

Molecules of that absorb specific wavelengths of IR energy experience different fates:

- **Some hold that extra energy for a brief time, then re-emit it in all directions as heat.**
- **Others collide with atmospheric molecules such as N_2 and O_2 and transfer the absorbed energy to those molecules, as heat**

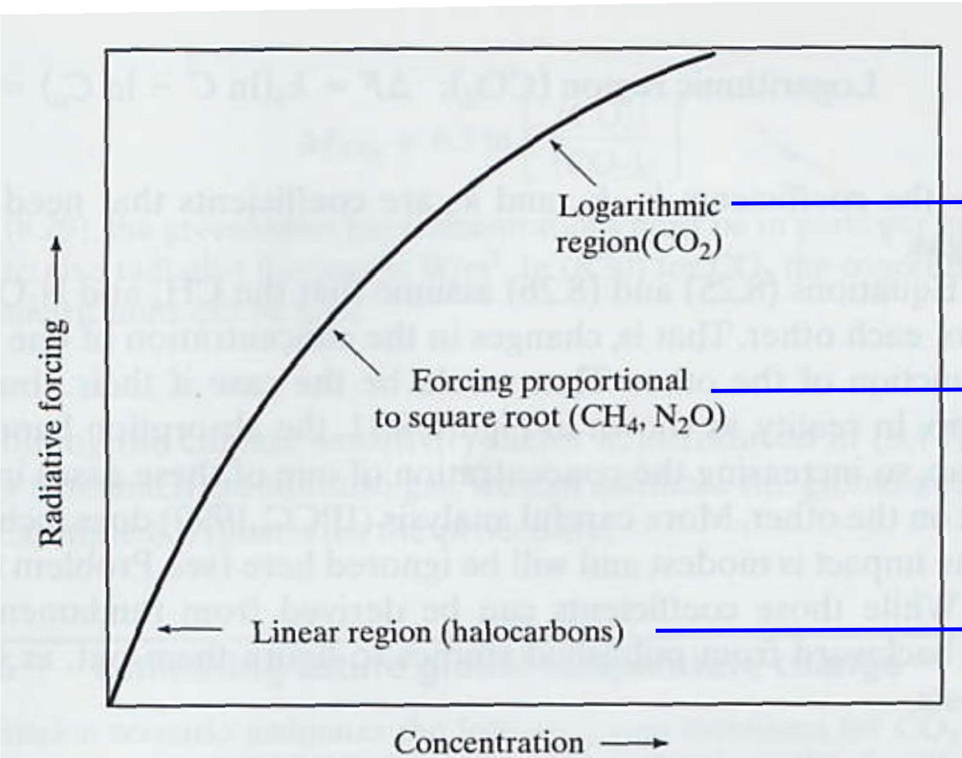
Both processes "trap" radiation emitted by the Earth; this trapping of energy heats the lower atmosphere and surface



Masters, Intro. to Environmental Engineering and Science, 3d ed.

See Chapter 3.4 by Dan Kirk-Davidoff,
in *Green Chemistry: An Inclusive Approach*, 2018
in Additional Readings for a simple, differential equation description of the GHG effect based on a so-called two layer model.

How does RF change with concentration?



Masters, Introduction to Environmental Engineering and Science, 1998

Wigley (1987)

$$\Delta RF = \alpha \ln\left(\frac{C}{C_o}\right)$$

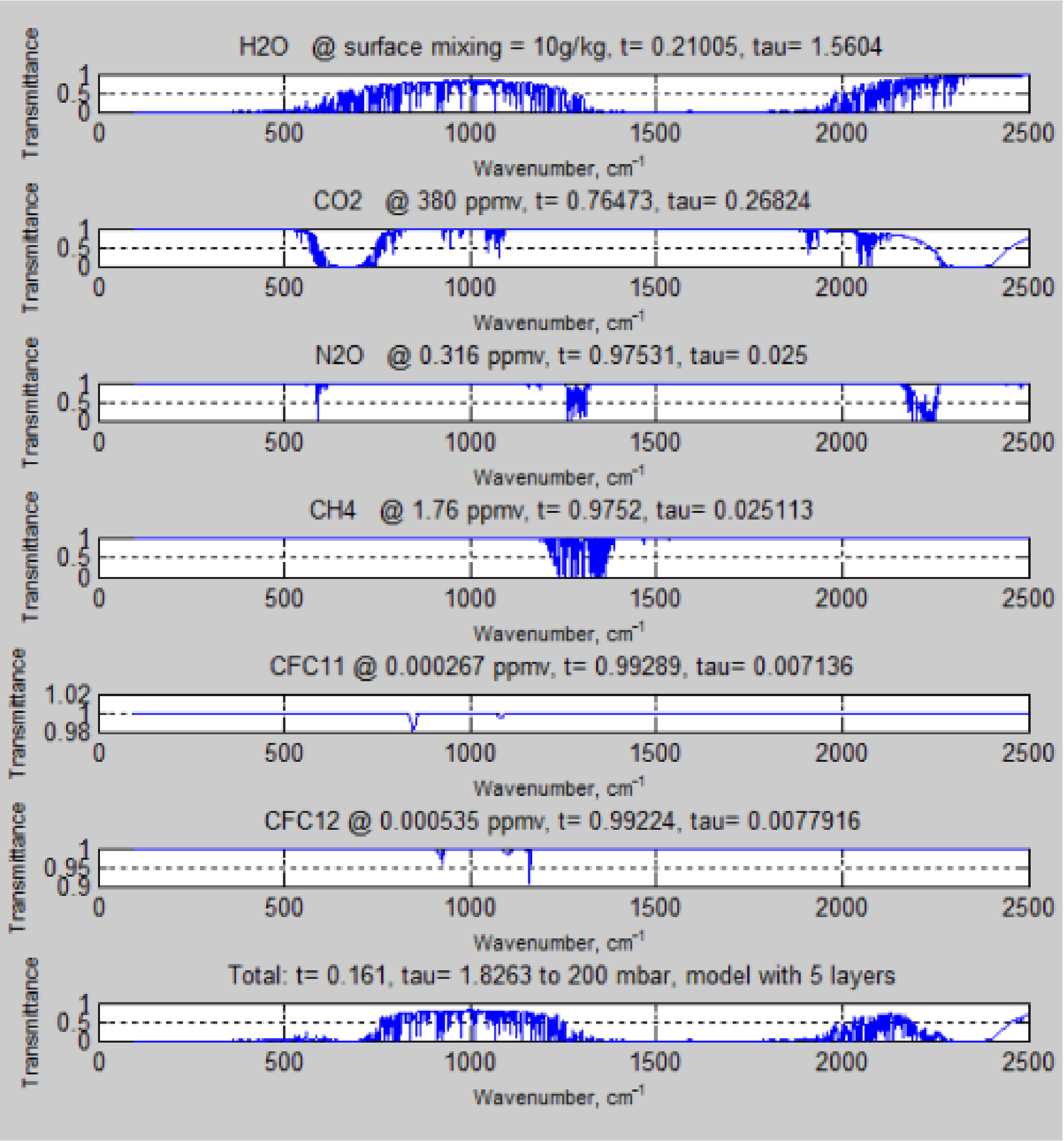
$$\Delta RF = \alpha \left(\sqrt{C} - \sqrt{C_o}\right)$$

$$\Delta RF = \alpha \left(C - C_o\right)$$

Effectiveness of a GHG depends on “saturation” of absorption band.

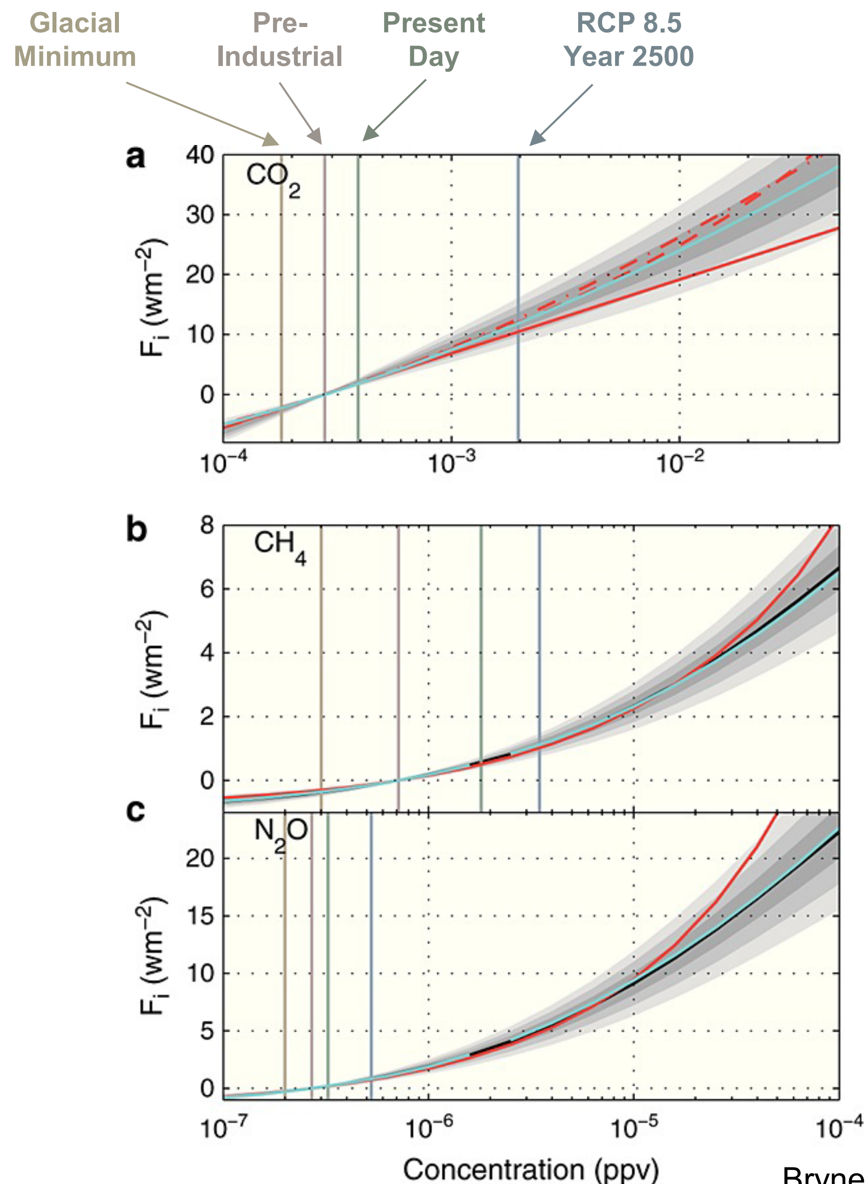
Highly saturated (most of the outgoing radiation is already absorbed) bands are less sensitive to increases in GHG concentration than partially or non saturated bands.

How does RF change with concentration?



https://scienceofdoom.com/2011/05/28/the-mystery-of-tau-–-miskolczi-part-six-minor-ghgs

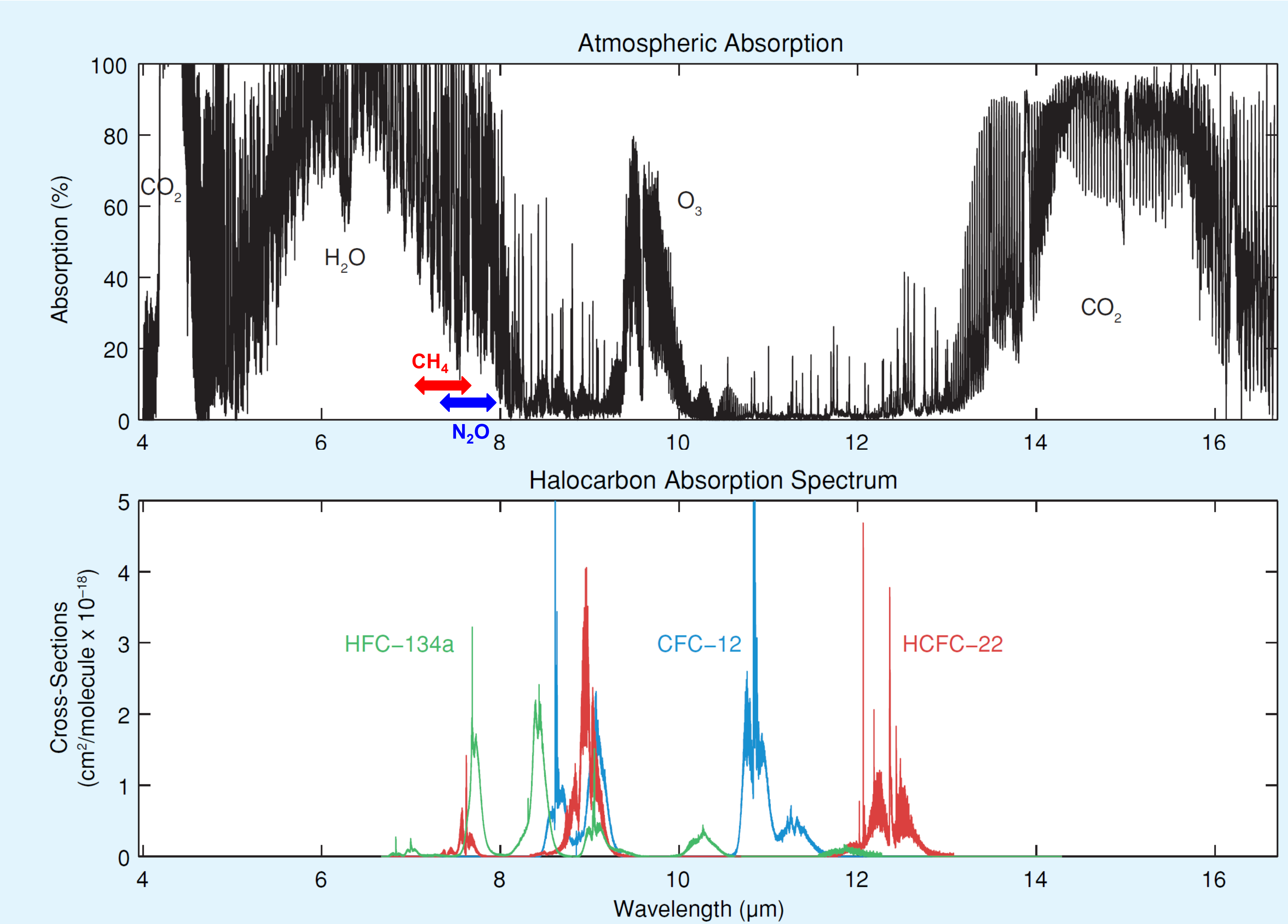
How does RF change with concentration?



- Black line is calculated RF using the Spectral Mapping for Atmospheric Radiative Transfer (SMART) radiative transfer code
- Light and dark grey show 1σ & 2σ uncertainties
- Cyan line is "fit" to the results
- Red lines are older fits from various IPCC and WMO/UNEP Ozone Depletion Reports

Bryne and Goldblatt, JGR, 2013
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013GL058456

Absorption vs. Wavelength



How does RF change with concentration?

These formulae have been used for AR3 (IPCC, 2001), AR4 (IPCC, 2007) and AR5 (IPCC, 2013). AR6 (IPCC, 2021) uses slightly different, more complicated formula to compute values of ΔRF that are shown in the next slide. In the Problem Set you're asked to compute ΔRF using the formula below.

$$\Delta \mathrm{RF\ CO_2} = 5.35 \ln\left(\frac{C}{C_o}\right) \mathrm{W\ m^{-2}}$$

$$\Delta \mathrm{RF\ CH_4} = 0.036 \left(\sqrt{M} - \sqrt{M_o}\right) - \left(f(M, N) - f(M_o, N)\right) \mathrm{W\ m^{-2}}$$

$$\Delta \mathrm{RF\ N_2O} = 0.120 \left(\sqrt{N} - \sqrt{N_o}\right) - \left(f(M, N) - f(M, N_o)\right) \mathrm{W\ m^{-2}}$$

$$\Delta \mathrm{RF\ CFC\text{-}11} = 0.25 \times \mathrm{CFC\text{-}11\ W\ m^{-2}} \quad \& \quad \Delta \mathrm{RF\ CFC\text{-}12} = 0.32 \times \mathrm{CFC\text{-}12\ W\ m^{-2}}$$

where

$$f(M, N) = 0.47 \times \ln\left[1 + 2.01 \times 10^{-5} (M \bullet N)^{0.75} + 5.31 \times 10^{-15} \bullet M \bullet (M \bullet N)^{1.52}\right]$$

C is mixing ratio of CO_2 in ppm

M is mixing ratio of CH_4 in ppb

N is mixing ratio of N_2O in ppb

CFC-11 and CFC-12 are mixing ratios of these species in ppb

& the subscript "o" refers to pre-industrial values of the respective mixing ratios

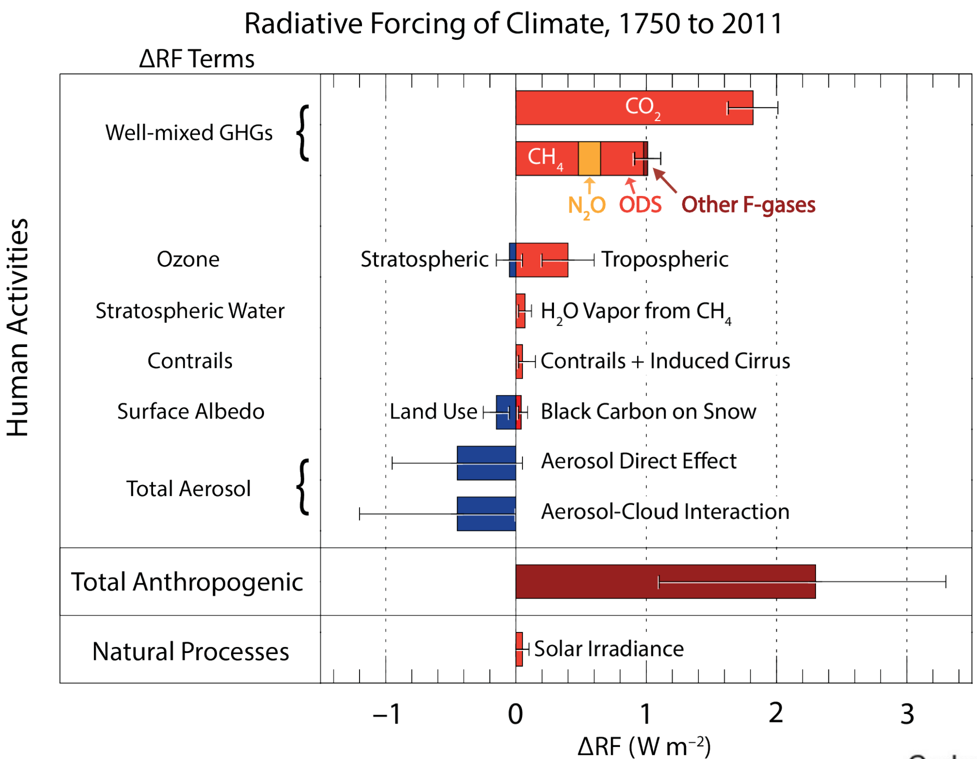


Figure 1.4, Paris Beacon of Hope

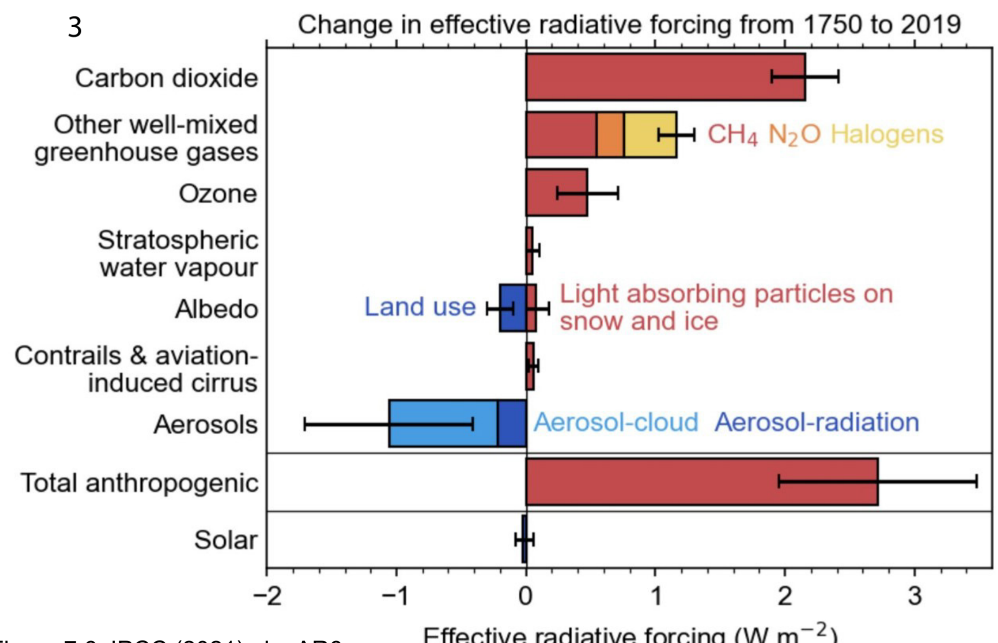


Figure 7.6, IPCC (2021) aka AR6

RF Due to Tropospheric Aerosols: Indirect Effect

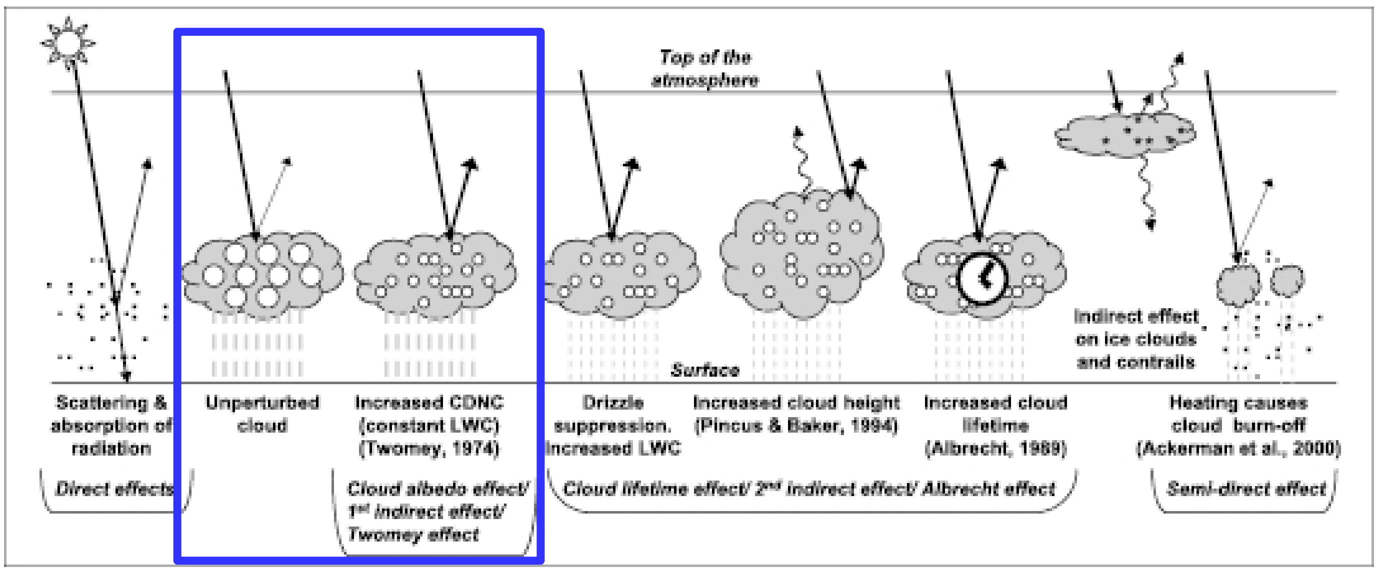
Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)

Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation

The cloud that is formed is therefore brighter (reflects more sunlight) ⇨

Twomey effect, aka 1st Indirect Effect



Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

RF Due to Tropospheric Aerosols: Indirect Effect

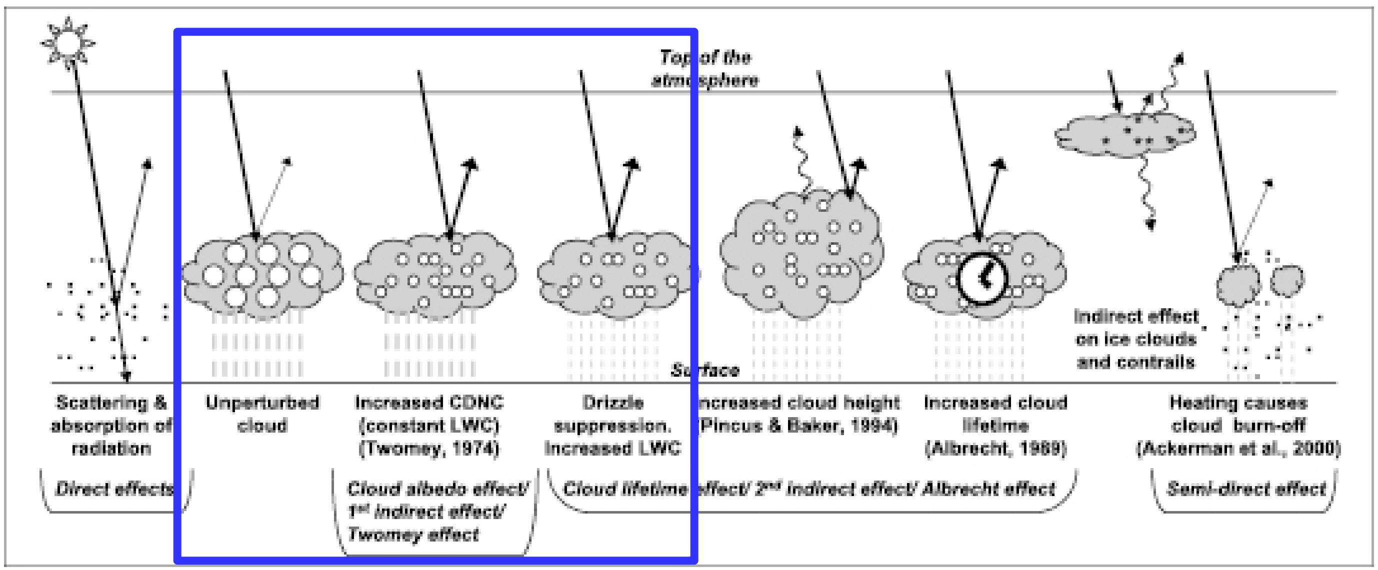
Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)

Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation

The cloud that is formed is therefore brighter (reflects more sunlight) ***and*** has less efficient precipitation, i.e. is longer lived) ⇨

Albrecht effect, aka 2nd Indirect Effect



Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Shared Socioeconomic Pathways (SSPs)

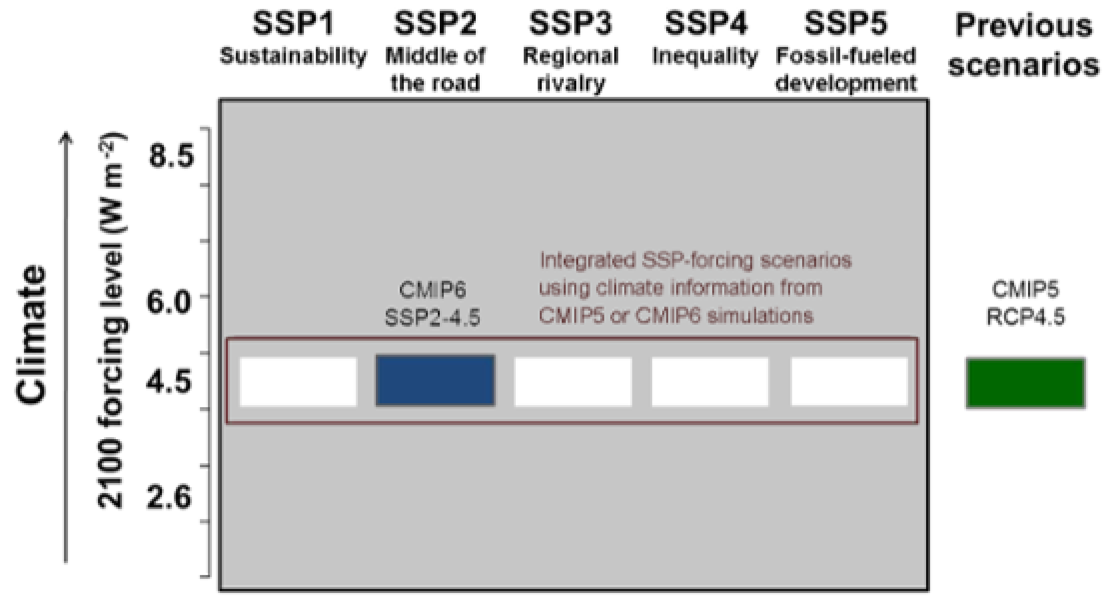


Figure 1. SSP forcing scenario matrix illustrating the combination of a 4.5 W m^{-2} forcing pathway with alternative SSPs. The dark blue cell illustrates a scenario serving as part of the design of ScenarioMIP. The green cell represents RCP4.5 in CMIP5, which was based on a previous emissions and land use scenario. White cells indicate scenarios for which climate information would come from either the CMIP5 or CMIP6 simulations.

O'Neill et al., 2016 https://gmd.copernicus.org/articles/9/3461/2016/gmd-9-3461-2016.pdf

Shared Socioeconomic Pathways (SSPs)

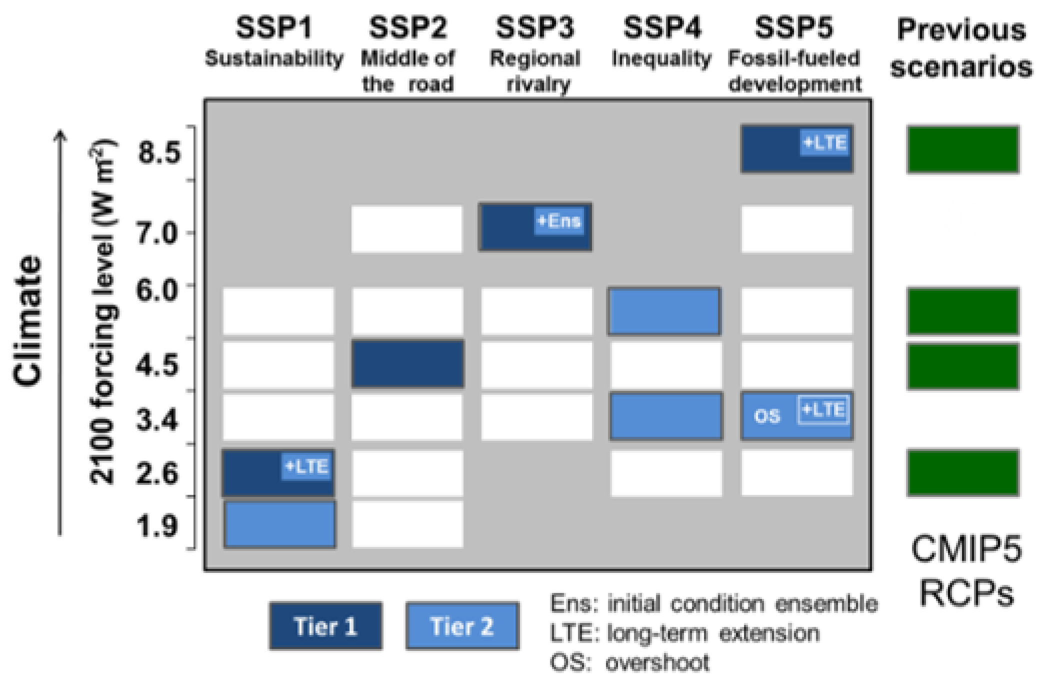
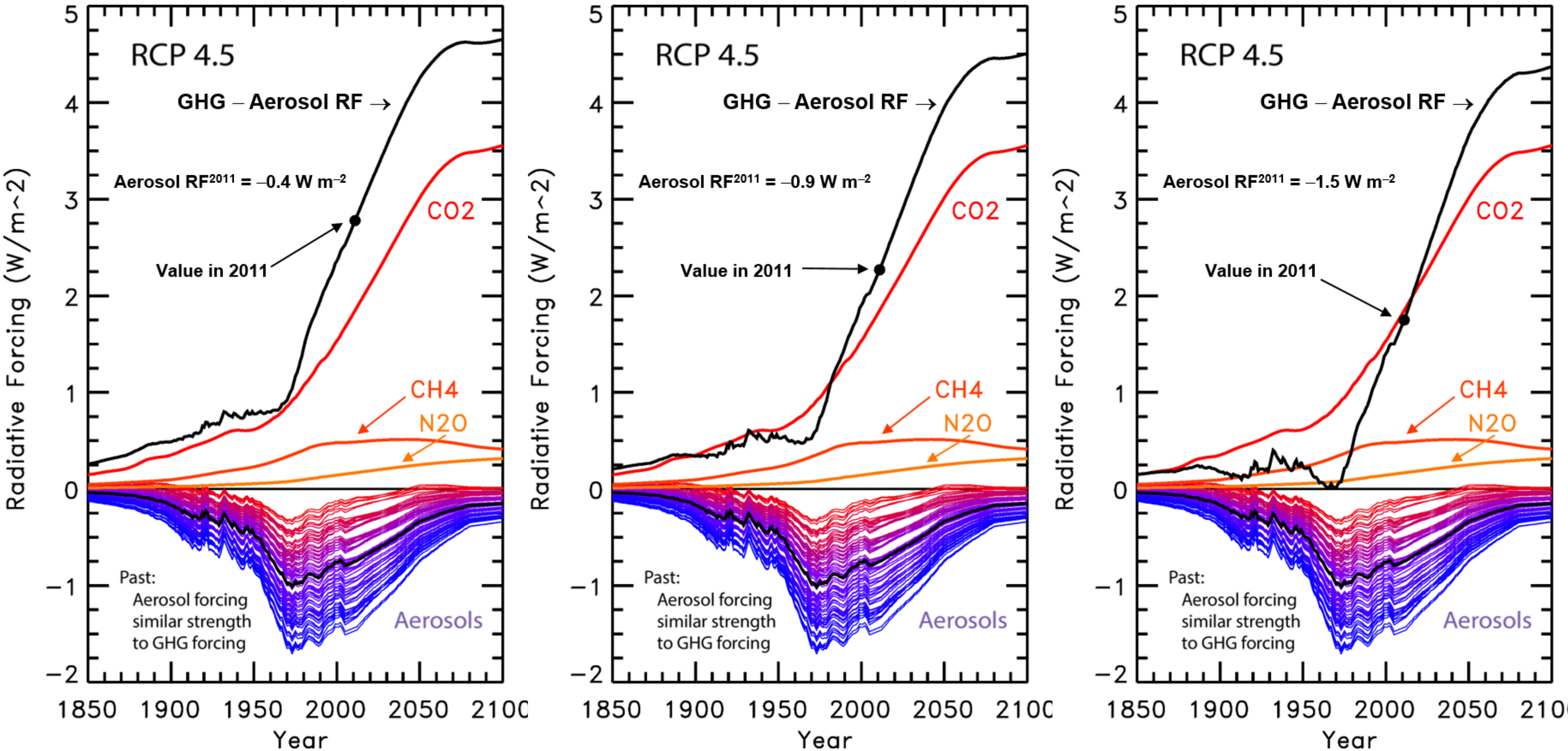


Figure 2. SSP-RCP scenario matrix illustrating ScenarioMIP simulations. Each cell in the matrix indicates a combination of socioeconomic development pathway (i.e., an SSP) and climate outcome based on a particular forcing pathway that current IAM runs have shown to be feasible (Riahi et al., 2016). Dark blue cells indicate scenarios that will serve as the basis for climate model projections in Tier 1 of ScenarioMIP; light blue cells indicate scenarios in Tier 2. An overshoot version of the 3.4 W m^{-2} pathway is also part of Tier 2, as are long-term extensions of SSP5-8.5, SSP1-2.6 and the overshoot scenario, and initial condition ensemble members of SSP3-7.0. White cells indicate scenarios for which climate information is intended to come from the SSP scenario to be simulated for that row. CMIP5 RCPs, which were developed from previous socioeconomic scenarios rather than SSPs, are shown for comparison. Note the SSP1-1.9 scenario indicated here is preliminary (see text).

O'Neill et al., 2016 https://gmd.copernicus.org/articles/9/3461/2016/gmd-9-3461-2016.pdf

Combining RF GHGs & Aerosols



Based upon Fig 1.10, *Paris, Beacon of Hope*

Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

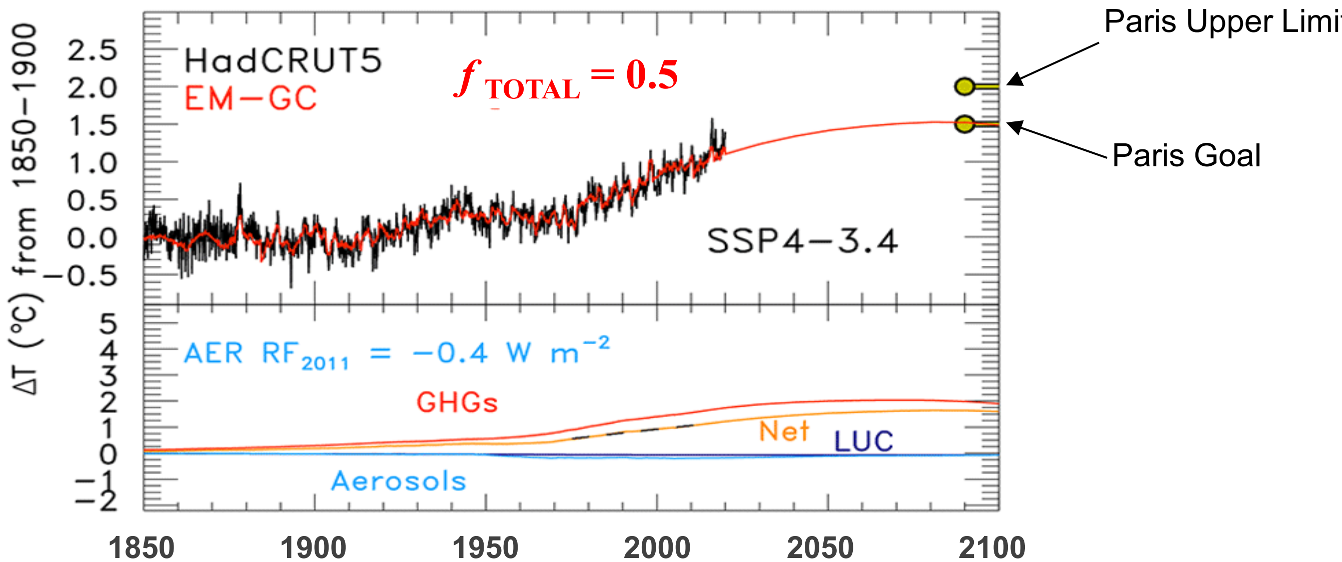
$$\Delta T = \lambda_{Planck} \times (1 + f_{TOTAL}) \times \Delta RF - OHE$$

where:

f_{TOTAL} = feedbacks due to water vapor, clouds, lapse rate, etc

OHE = ocean heat export

Lecture 2



McBride *et al.*, 2021
https://esd.copernicus.org/articles/12/545/2021

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.4 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of <u>other feedbacks</u> (clouds, surface albedo) must be ***close to zero.***

Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

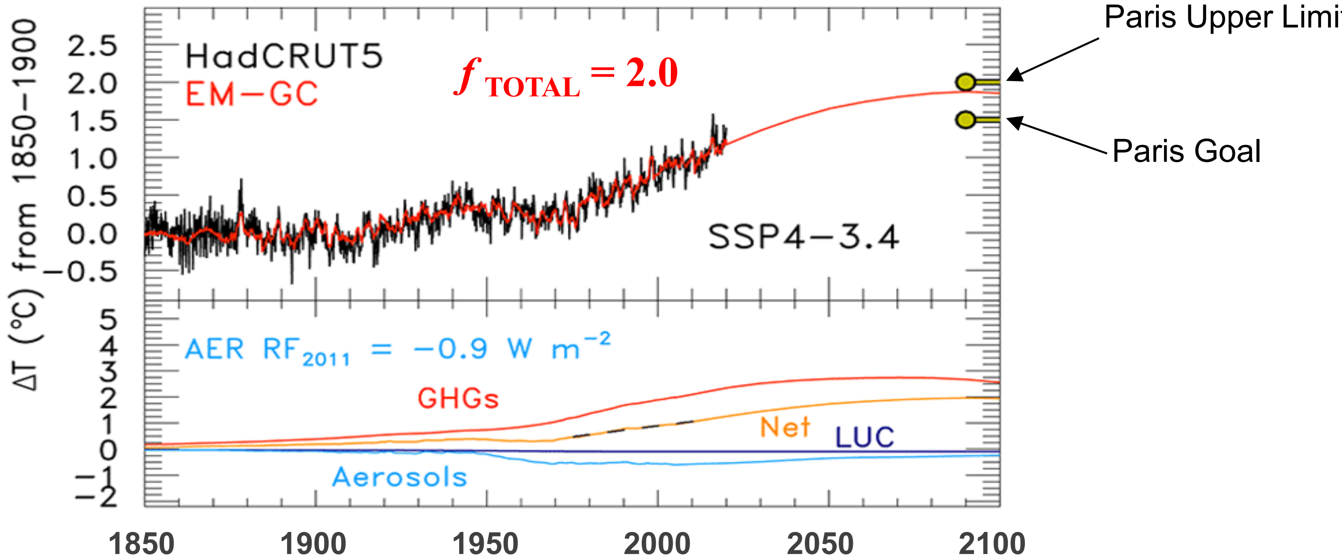
$$\Delta T = \lambda_{Planck} \times (1 + f_{TOTAL}) \times \Delta RF - OHE$$

where:

f_{TOTAL} = feedbacks due to water vapor, clouds, lapse rate, etc

OHE = ocean heat export

Lecture 2



McBride *et al*., 2021
https://esd.copernicus.org/articles/12/545/2021

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.9 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of <u>other feedbacks</u> (clouds, surface albedo) must be ***strongly positive***.

Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

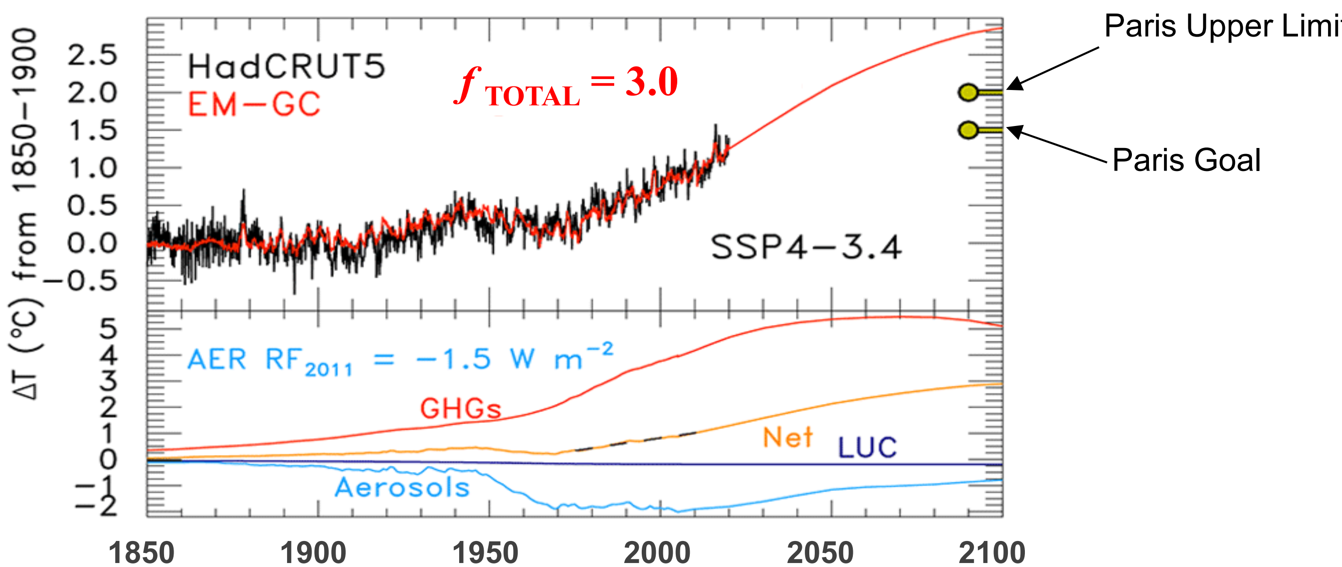
$$\Delta T = \lambda_{Planck} \times (1 + f_{TOTAL}) \times \Delta RF - OHE$$

where:

f_{TOTAL} = feedbacks due to water vapor, clouds, lapse rate, etc

OHE = ocean heat export

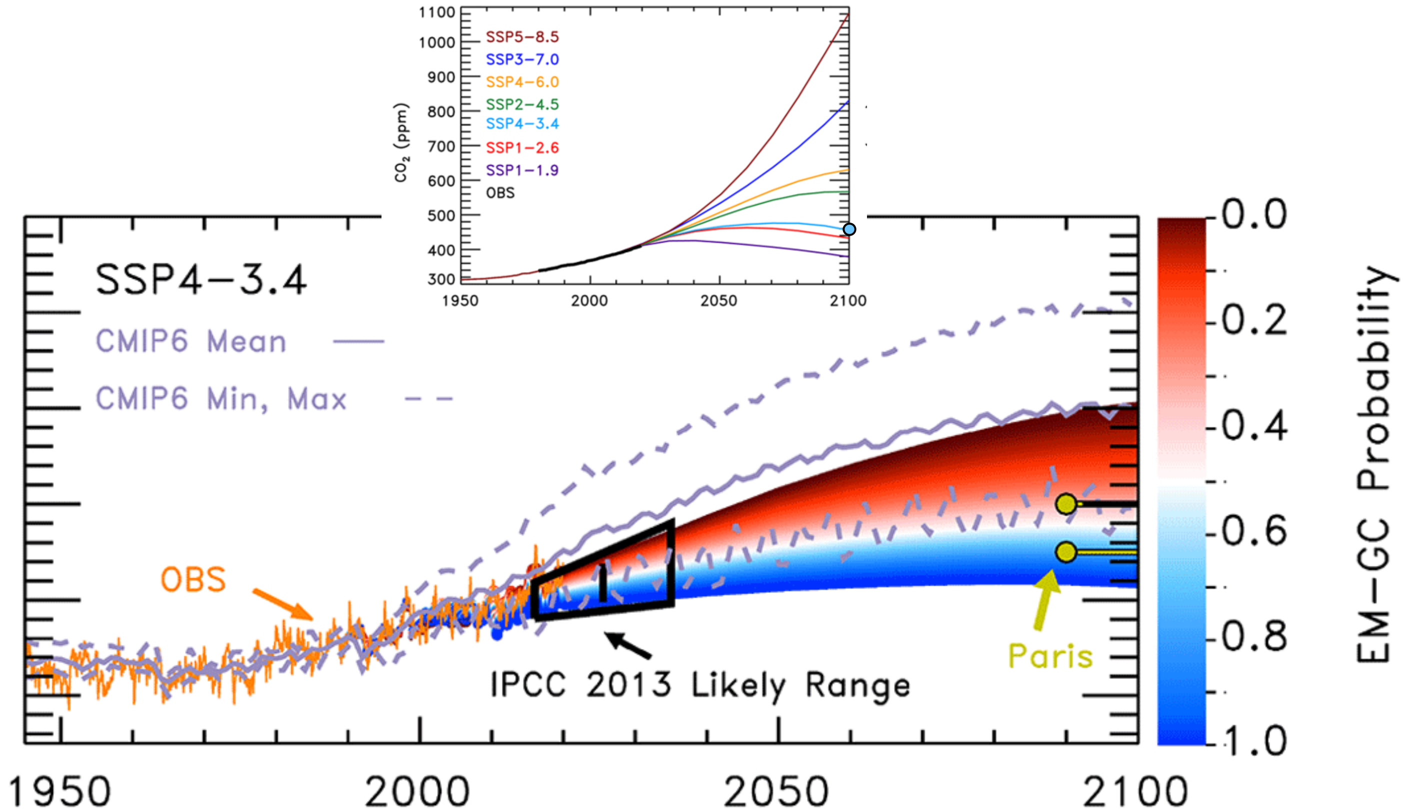
Lecture 2



McBride *et al*., 2021
https://esd.copernicus.org/articles/12/545/2021

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **–1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***very strongly positive***.

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP4-3.4

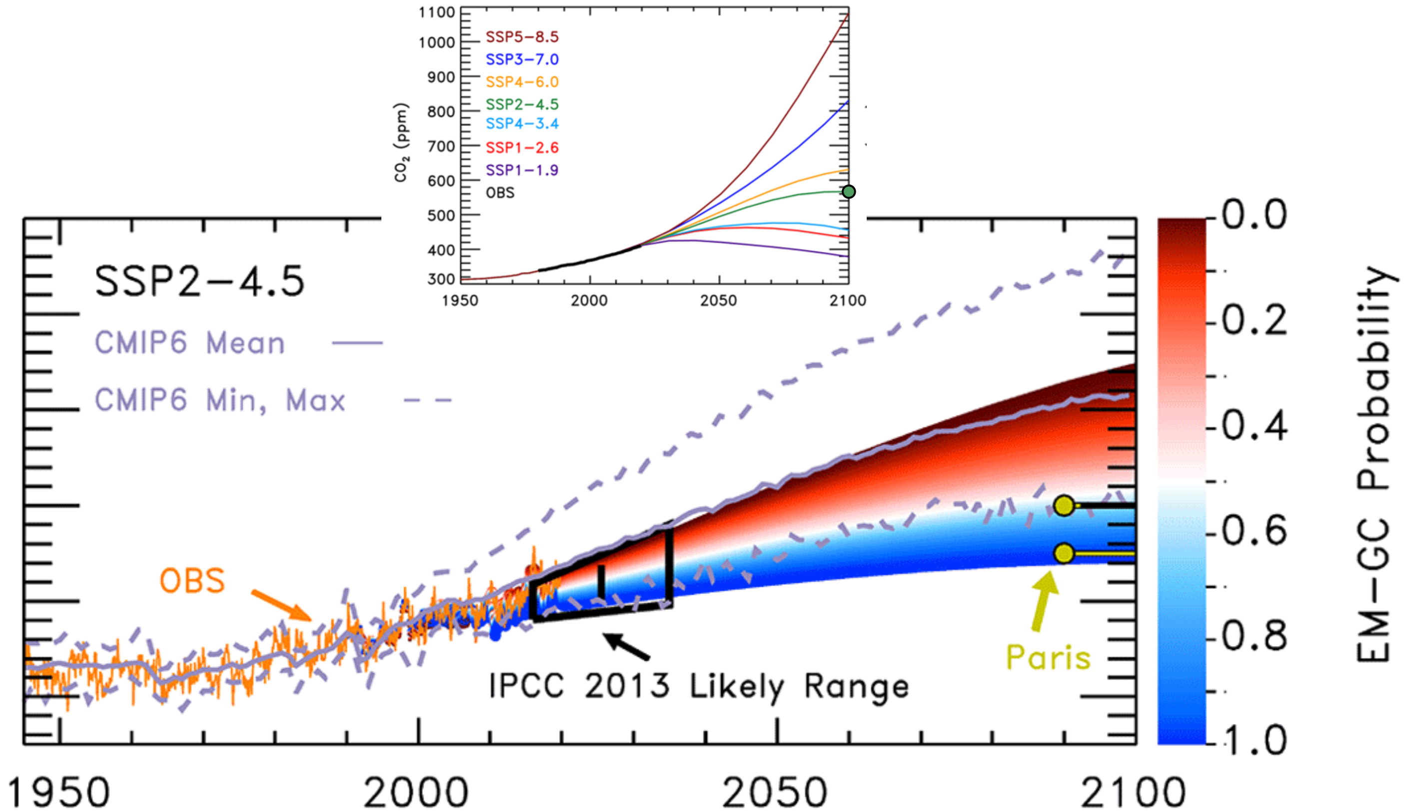


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP2-4.5

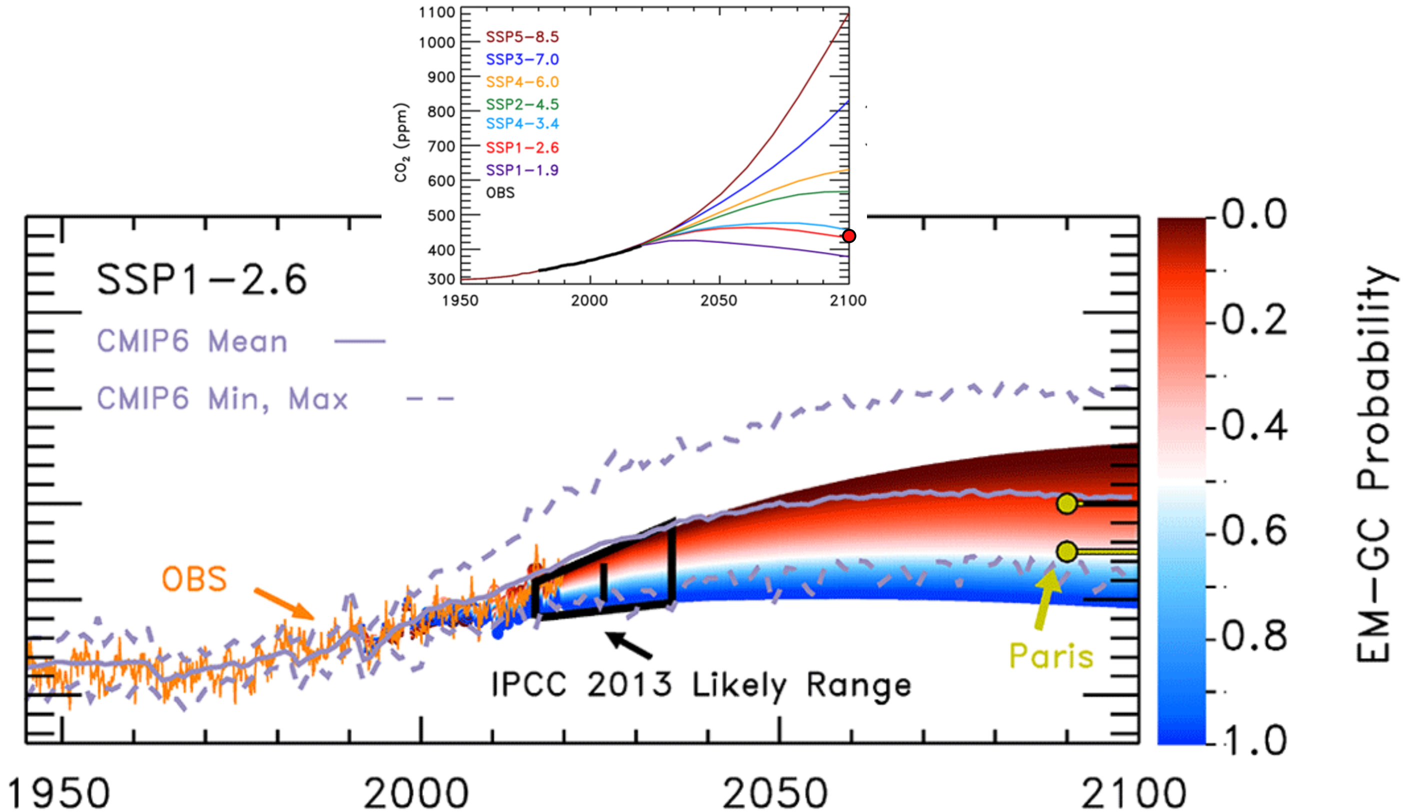


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-2.6

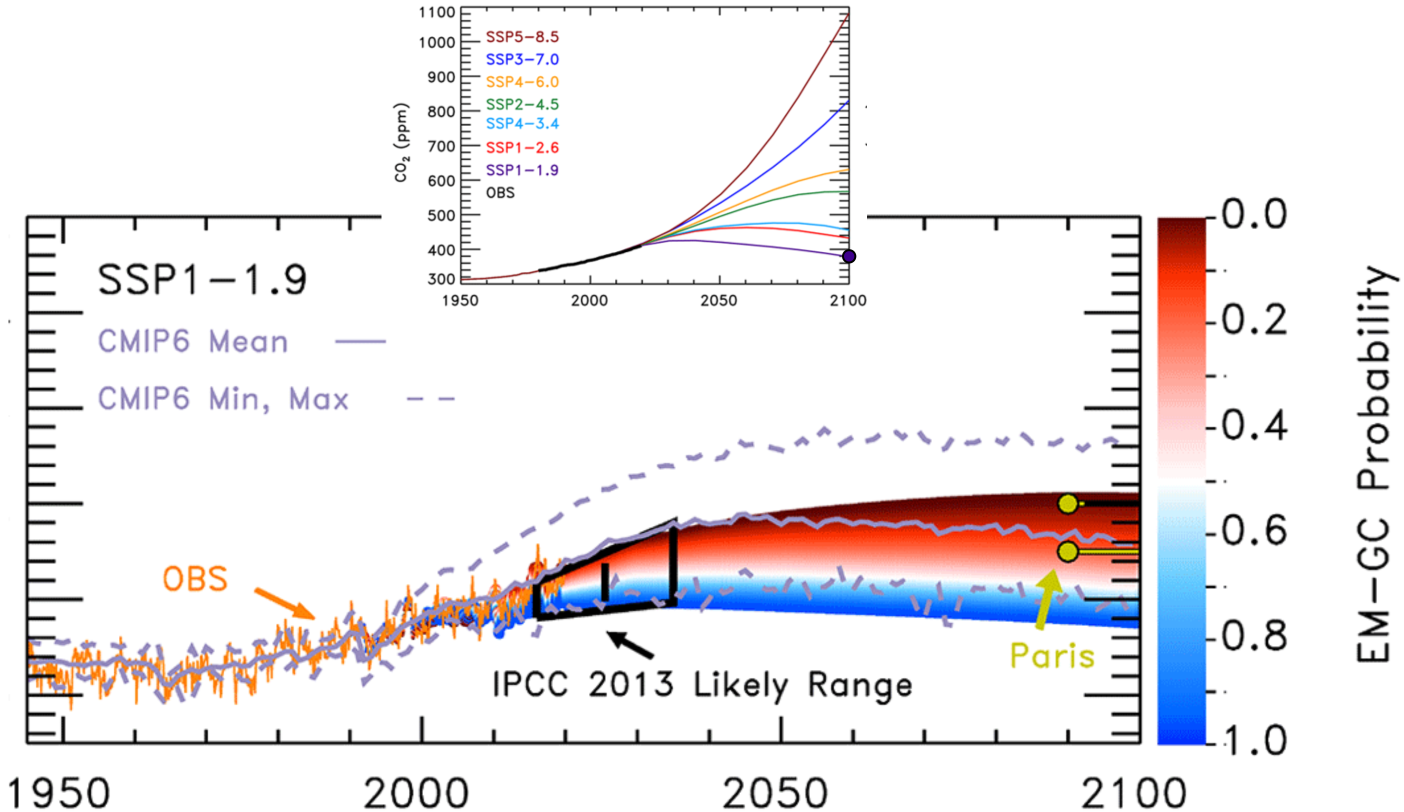


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-1.9



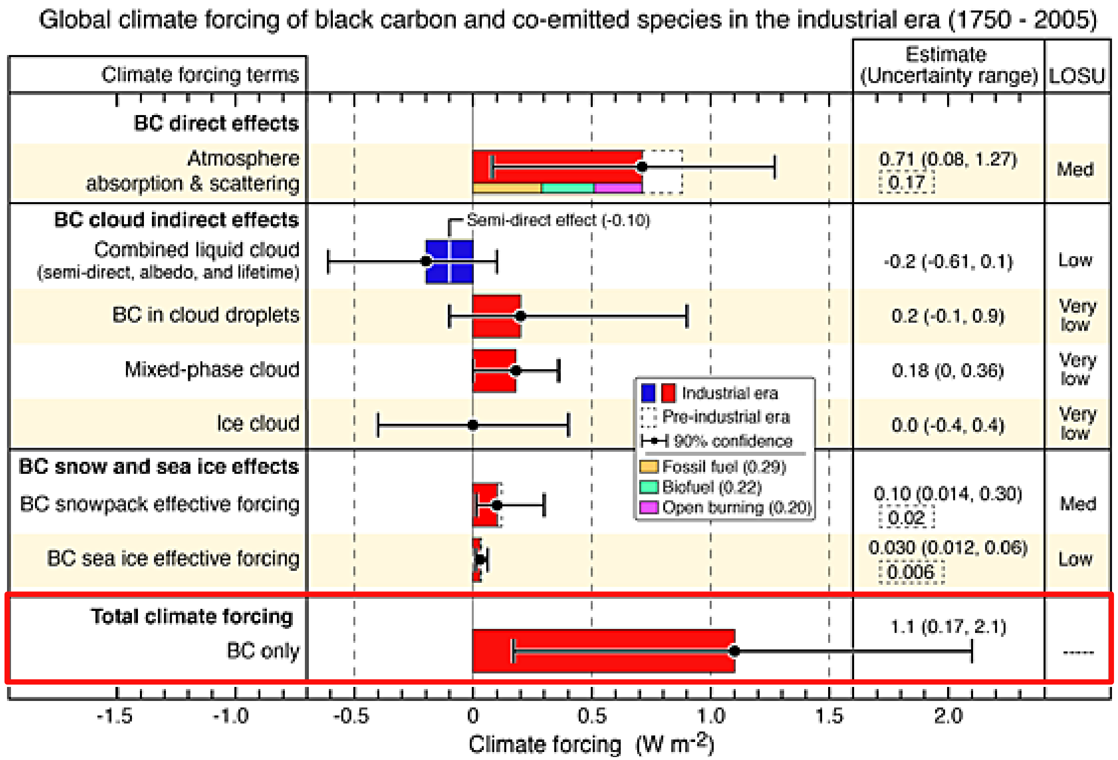
If GHGs follow SSP1-1.9, **81%** chance rise GMST stays below **1.5°C** and **98%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Black Carbon Aerosols

Bond *et al*., Bounding the role of black carbon in the climate system: A scientific assessment, *JGR*, 2013



	Total Climate Forcing, Black Carbon Aerosols		
Report →	IPCC (2007) for 1750 to 2005	IPCC (2013) for 1750 to 2011	IPCC (2021) for 1750 to 2019
ΔRF, BC→ Numbers in "( )" are upper and lower limits	0.2 (0.05 to 0.35) W m^{-2}	0.4 (0.05 to 0.80) W m^{-2}	0.11 (–0.20 to 0.42) W m^{-2}